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THE INVENTION AND DEVELOPMENT OF PLACER

FORREST J. AGEE, Ph.D
HUEY A. ROBERTS, Ph.D
HARRY DIAMOND LABORATORIES
ADELPHI, MD 20783

INTRODUCTION.--The importance of hardening the SAFEGUARD System to EMP was established in the turbulent arguments of complexity and potential vulnerability of any ABM system during the deployment debates of the late 1960s. During the course of the considerable effort to achieve the operational Grand Forks Tactical Site, a unique problem was posed by the over 40 miles of buried conduits which formed part of the shielding for the control and power cables connected to each missile cell. Since these conduits were buried less than a skin depth deep, they constituted major receiving antennas for EMP and lightning. It was recognized that a nondestructive test technique was needed that would permit verification of the shielding provided by the conduits, initially to verify adequacy of construction, and periodically through the system life to insure that rust, freezing, or ground movement had not degraded the conduit system in such a way as to compromise the protection afforded by it. The Harry Diamond Laboratories was tasked by the SAFEGUARD Systems Command to develop such a technique. A survey of methods used by oil companies, power companies, and other users of pipelines and conduits disclosed that no technique was available which would be suitable for an EMP threat-relatable assessment. A program was initiated to proceed through several phases to identify possible approaches, to experimentally evaluate the most promising ones, and to develop and field the one most suited for inclusion in the SAFEGUARD Protection Integrity Maintenance Program (PIM). Shortly after the PIM Program began, water was discovered pouring out of some of the power and communications conduits during cable pulling at the missile fields, and a sense of urgency and increased visibility were added to the effort.

Technically, the problem was to test the shielding provided by 2-and 4-in. steel conduits containing power or control cables buried at depths from 6 to 12 ft and to determine how to measure the effects of single and multiple flaws in the conduits when exposed to EMP from a high-altitude nuclear burst. The conduits were laid in a network of conduit banks of varying cross section with as many as 35 conduits near terminal structures and eventually as few as one or two conduits at the entry points to missile launch stations. The conduits were located at five missile sites with typical conduit lengths varying from 100 to 500 ft between shielded structures (manholes, terminal structures, control buildings, and missile cells). As the conduit banks proceeded from power or control cable distribution points out into the missile fields, groups of conduits were directed away from the main conduit runs at manhole structures or at branch points in the missile fields. This situation posed a complexity in terms of conduit current sharing which had to be resolved to conduct a threat analysis. Since the conduits were buried in earth in close proximity (compared to a skin depth for wavelengths of interest for EMP) in the conduit banks, it was clear that there should be some current sharing, with outer conduits probably carrying more of the current than inner ones. What was not clear was how the sharing would go and how to account for it in relating any kind of test data to the EMP threat, which had been formulated analytically in terms of the current which would be induced on a single conductor, taking into account soil conductivity, depth of burial, and other relevant parameters. Little was known about what kind of flaws might exist in conduit systems which would be important from an EM shielding standpoint. It was apparent that a detailed knowledge of classes of probable types of flaws would be required since it was improbable that a technique would be developed which would exactly duplicate an EMP excitation. Hence, supporting analysis would require a knowledge of characteristics of flaws as a function of frequency and amplitude. To this end, a program of field and laboratory tests on conduits and types of possible flaws was undertaken at the Woodbridge Research Facility. The program began with studies of a single buried conduit and laboratory transmission-line measurements on single flaws and progressed in stages to more complicated field test models. Since the conduits were constructed by joining 10-ft lengths of steel pipe together with threaded couplings and unions, several joint-type flaws were possible, including rusted threads and loose and misaligned unions, as well as cracked, fractured, rusted, or improperly assembled conduit sections and flex-joints.

It was decided to concentrate the HDL resources on EM techniques, since these appeared to offer the greatest potential for achieving a threat-relatable assessment. Another factor was that other organizations were conducting visual inspections of the interior of the conduits by use of miniature television cameras and doing air-leak testing. Altogether, five EM techniques were tried out on the single and five conduit test models, which contained various flaws (broken conduit, rusted couplings, and the like). Two CW techniques (1,2) were evaluated through contractor efforts and three time-domain techniques were tried using HDL developed simulation equipment which was tailored to suit the conduit application. CW techniques were found to be inferior to the pulsed techniques in testing at the conduit test models, especially when multiple flaws were present in a conduit.

THE INVENTION OF PLACER.--Figure 1 shows a dual-loop version of Pulsed Loop Antenna Conduit Electromagnetic Radiator (PLACER) used during the preliminary experiments to excite a buried conduit. The loops were driven in parallel by discharging a storage capacitor across a spark gap in series with each loop terminated in 40 ohms. Thus PLACER was simply a pulse-driven series LRC circuit. The initial experiments were conducted using a test model which consisted of a 2-1/2-in. ID conduit, 100 ft long, which was buried at a depth of 3 ft. One end of the conduit was secured to a shielded instrumentation box, while the other end was sealed with a threaded end cap. Both ends of the conduit were grounded using 4-ft-long ground rods driven into the earth. Conduit current was measured by using a clamp-on type of current probe. Inside the conduit, a cable (sense wire) extended the entire length of the conduit and was terminated in the characteristic impedance of the conduit-sense-wire transmission line. Current which was coupled onto the sense-wire at the conduit flaw was monitored inside the shielded enclosure by using an oscilloscope and a camera. The oscilloscope was powered by a storage battery and invertor.

In order to couple current onto the conduit, PLACER was positioned about 1 ft aboveground and parallel to the ground. When the center of the loop was directly over the buried conduit, the conduit current was zero, and the current was observed to reverse polarity as the loop was moved in a perpendicular direction across the conduit. In this manner, it was possible to locate the buried conduit very precisely by observing the nulling effect in the conduit current or in the sense-wire current when a conduit flaw was present. The optimum range for coupling the maximum current onto the conduit was 5 ft between the center of the loop and the point

directly above the conduit opposite PLACER. Figure 2 shows the waveform of the conduit current which was measured opposite PLACER when it was positioned 5 ft from the conduit. The breakdown voltage was 85 kV.

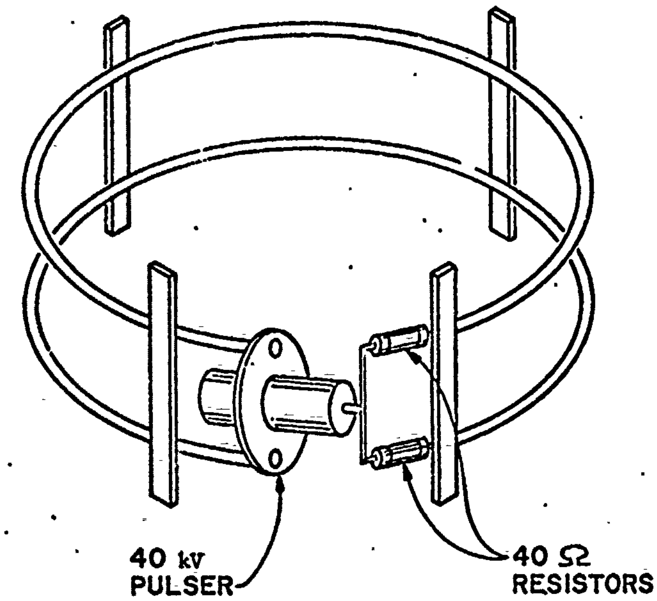

Figure 1. Experimental Dual-Loop Version of PLACER.

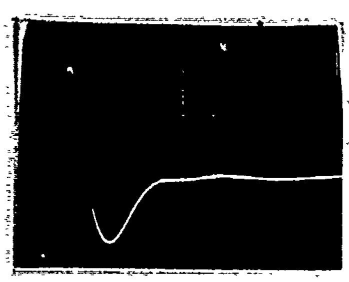

Figure 2. Conduit Current Waveform, 26.6 A/div, 500 ns/div.

During the course of the preliminary experiments, several spark gap pulsers were used to drive the 9-ft-diameter, two-turn parallel loop antenna. The pulser breakdown voltage and storage capacitance were varied to determine their influence on the current coupled onto the buried conduit. The peak conduit current increased linearly as the breakdown voltage was varied from 20 to 100 kV; however, the conduit current waveform was not significantly different for a storage capacitance of 5nF, 0.3 μF or 1μF. Hence, the waveform was determined primarily by the loop diameter and the combined 20-ohm load resistance used throughout the experiments.

Figure 3 shows a cutaway view of the experimental arrangement for the preliminary evaluation of the PLACER technique for locating conduit flaws, using the single buried conduit. The conduit fault was a 5-in. transverse slot introduced into the conduit. The sense wire was lying inside the 2-1/2-in. ID conduit opposite the upward turned slot. The variation of the peak conduit current with perpendicular range from the conduit is shown in figure 4. With PLACER positioned at the optimum distance of 5 ft from the conduit, PLACER was moved parallel to the conduit. The peak conduit current for the parallel sweep along the conduit is shown in figure 5. A similar plot of the peak sense-wire current resulting from the transverse slot is shown in figure 6. The strong peaking effect shown in figures 5 and 6 resulted from the combined effects of the localized excitation from the loop antenna and the attenuation of the current pulses as they propagated down the conduit, which was surrounded by the lossy earth medium. The more pronounced peaking effect in the sense-wire current resulted from the fact that the slot preferentially coupled higher frequency current onto the sense wire. When a rusted coupling was introduced as the conduit flaw, the peaking effect and the waveform of conduit and sense-wire currents were similar (data not shown).

SAFEGUARD SYSTEM DEVELOPMENTAL TESTING.--In October 1973 a significant opportunity was exploited to test the feasibility of the three best approaches at one of the Sprint Launch Sites (RSL 1) as an added effort in an EMP test. This test also provided a vehicle to resolve the current sharing problem. In support of a Corps of Engineers program to evaluate the hardening provided by the site construction, HDL developed a portable 250 kV biconic-dipole repetitively pulsed simulator (fig. 7) which could be suspended from a crane. The test plan was expanded to include digging two shafts so that conduit current measurements could be made during the EMP testing on a bank containing 20 conduits. In addition, it was possible to arrange for clamp-around current probes to be attached to conduits at the Missile Site Radar (MSR)

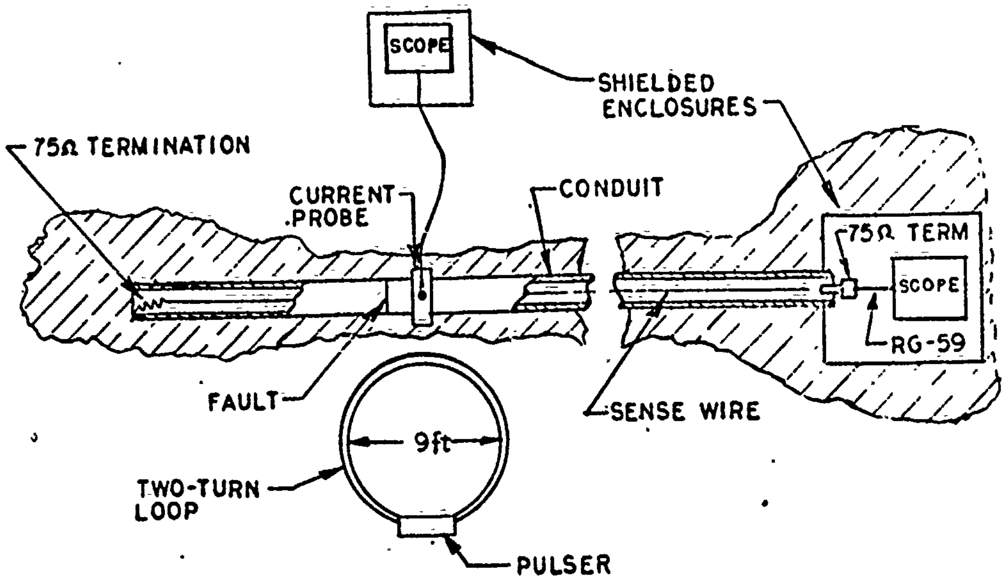

Figure 3. Cutaway View of Single Buried Conduit Test Model.

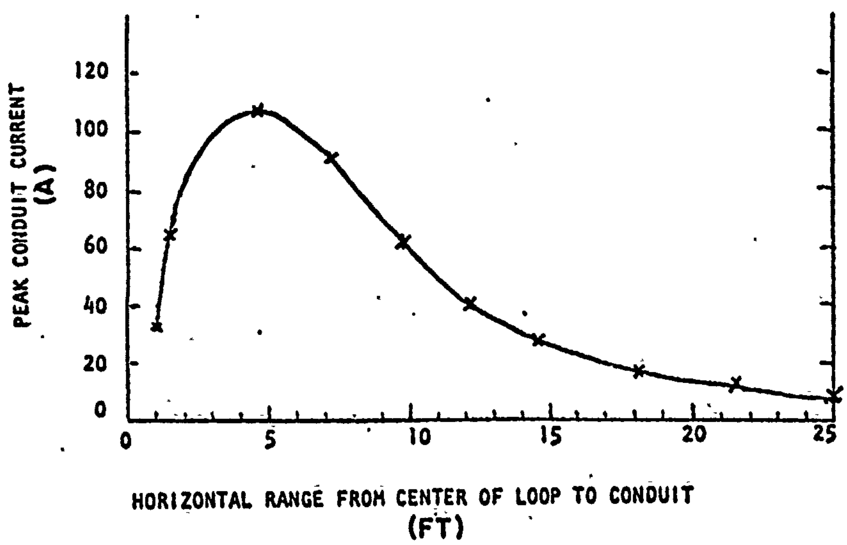

Figure 4. Peak Conduit Current Variation With Range from 85-kV PLACER.

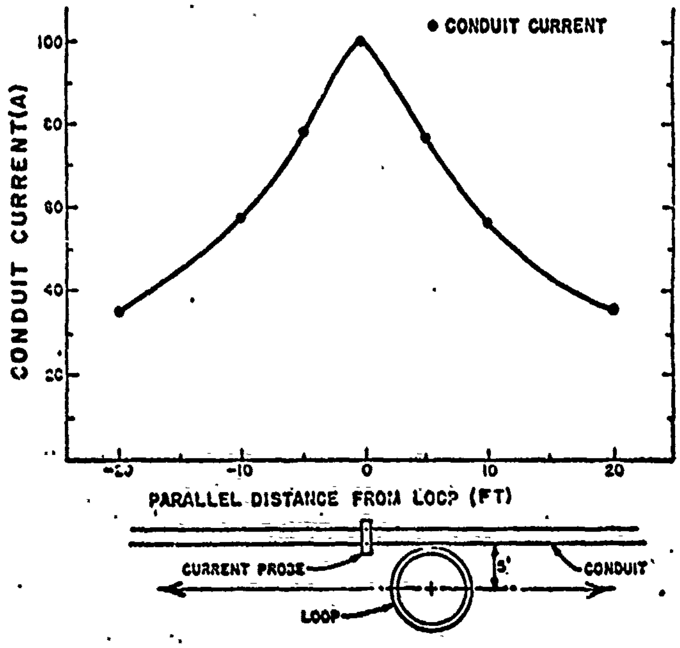

Figure 5. Peak Conduit Current for Parallel Sweep at Range of 5 ft.

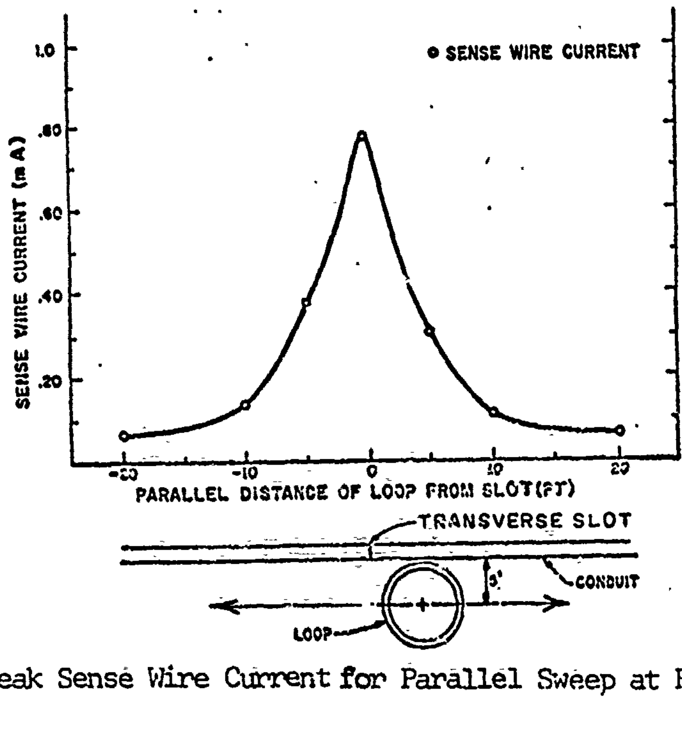

Figure 6. Peak Sense Wire Current for Parallel Sweep at Range of 5 ft.

Collocated Missile Field so that PIM experimentation and calibration could be conducted there as well as at the RSL 1 test site. The tests were made possible by the expedited development of 5-in. window Stoddart current probes which were sized to fit in the conduit banks.

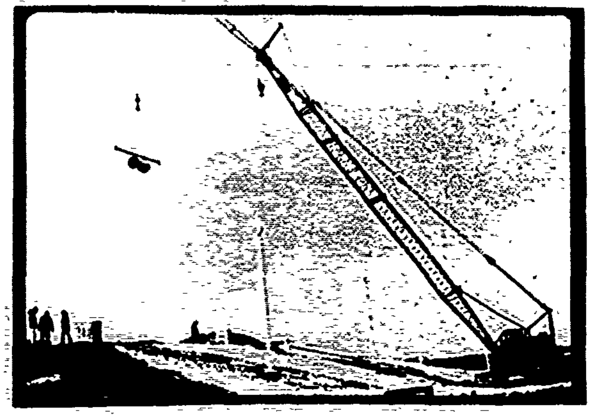

Figure 7. 250-kV Bicone-Dipole EMP Simulator at RSL 1.

The conduit testing at RSL 1 consisted of conduit current measurements with the conduits excited by the bicone-dipole simulator (fig. 7) and by the 85-kV version of PLACER (fig. 1). The conduit current measurements indicated that both the EMP simulator and the pulsed loop exhibited similar conduit current distributions among the conduits in the bank and that the greatest current in both cases appeared on corner conduits, with outer conduits having the effect of shielding inner ones, as expected. Subsequent measurements on a single buried conduit in the vicinity of a missile cell showed that the current on a top corner conduit in a bank was 25 percent of that induced on a single buried conduit. These data provided the scaling needed to relate test calibration data taken on a top corner conduit to the single buried conduit analytical threat current, as well as providing a direct accounting for conduit current sharing. The testing at RSL 1 also provided a bonus which was to be significant to the program. The conduit illumination by the EMP simulator was being monitored by measurements of current induced on Launch Enable and Status Order (LE and SO) cables inside the Remote Launch Operations Buildings (RLOB). It was discovered that relatively large currents were coupled onto the cables inside the conduit leading to Sprint Cell 8. This discovery did not correlate with the results of earlier air-leak

testing, which had not identified a major air leak in this conduit but had indicated only a minor one near the RLOB. This provided an opportunity to demonstrate PLACER flaw location technique in situ in a missile field; however, there were several difficulties which had to be overcome.

The construction and equipment installation activities underway at the time precluded EMP test operations except at night at RSL 1. The PIM activities constituted therefore an added effort to an already time-constrained test schedule, and the presence of additional current and field pulses from the loop could conceivably interfere with the principal test objectives. Consequently, the PLACER testing had to be conducted on a noninterference basis with the EMP test. The early experimental version of PLACER was then configured so that it had to be taken apart to be moved. This problem was overcome by constructing a crude sled of plywood and two-by-fours and by tying the pulser and antennas to the sled. The weather during the testing was seasonal for October and November in North Dakota. The 20-knot winds and near zero temperatures combined with the snow had been a hindrance up until this point. However, the snow and ice made it somewhat easier to drag the sled alongside the locus of the conduit bank. The major flaw was located very near the missile cell, and a minor flaw was also located near the RLOB. The PLACER technique described earlier caused a current nulling when the antenna was directly over a conduit and a reversal when it was moved to the opposite side of the conduit. This property was used to verify that the flaw was in the conduit itself rather than a shielding deficiency in the missile cell.

The supplementary testing at the MSR Collocated Missile Field verified that three pulsed techniques (the pulsed transmission line, the pulsed dipole (3) and PLACER) were capable of driving adequate currents on conduits for testing and further verified the test calibration approach which was adopted. The unique ability of PLACER to locate flaws as well as to indicate their presence and magnitude led to further development of PLACER as the test technique for both the initial assessment and subsequent PIM testing of the missile field conduits.

THREAT ANALYSIS.--While the PLACER technique is adequate for detecting and locating conduit flaws, it does not simulate a nuclear EMP environment. The frequency content of PLACER induced conduit current is limited by the loop dimension, while the current amplitude is determined by the breakdown voltage of the spark gap. Therefore, a threat-relatable conduit assessment using the PLACER

requires additional and complementary information concerning the characteristics of conduit flaws and propagation of currents within the conduit system.

The current induced on an interior cable at the site of a conduit flaw can be described in terms of a flaw impedance (a characteristic of the flaw), the current on the outer surface of the conduit, and the characteristic impedance of the conduit-cable transmission line. In the frequency domain, these quantities are related by

$$(1) \quad I_o(w) = \frac{I_c(w)\ Z_F(w)}{2Zo + Z_F(w)}$$

where w is the angular frequency, $I_o(w)$ is the induced current, $I_c(w)$ is the conduit current, $Z_F(w)$ is the flaw impedance, and Z_o is the characteristic impedance of the conduit-cable line. The total cable current at any point y in the conduit system can then be expressed as

$$(2) \quad I_s\ (w,y) = I_o(w)\ H(w,y)$$

where H(w,y) is the Fourier transform of the system response to a unit impluse current. The system function H(w,y) is completely determined by the transmission-line characteristics and load impedance of the conduit-cable line. For most cable configurations at SAFEGUARD, H(w,y) is derivable from simple transmission-line considerations. In other cases of interest, the impulse response can be determined by observing the PLACER induced cable current at selected points along the cable route. Considering the length of the cables (500 to 1500 ft), the PLACER induced conduit current (and hence induced cable current) approximates an impulse (4).

Equation (2) can be readily transformed to express the total cable current as a function of time. The calculated cable current can then be compared with the current levels which cause upset or damage to the system. These current levels have been determined by the weapons system contractors (5,6).

In most cases, Z_F is much less than Z_o. When it is not, the cable current becomes comparable to the conduit current, in which case the conduit should be repaired. For the special case of a completely broken conduit, Z_F is infinite, and equation (1) becomes $I_o(w) = I_c(w)$.

Equation (1) can be rewritten for the case $I_o \ll I_c$ (small flaws):

$$(3) \quad Z_F(w) = \frac{2Z_o\, I_o(w)}{I_c(w)}\ , \text{ or } \quad \frac{Z_F(w)}{2Z_o} = \frac{I_o(w)}{I_c(w)}\ .$$

Therefore, in order to characterize each type of conduit flaw, it is sufficient to measure $I_O(w)/I_C(w)$ over the appropriate frequency range. A study of the conduit flaw characteristics was conducted in the laboratory (4). These experiments used current injection techniques to couple current onto the outer surface of a short section of conduit into which flaws were introduced one at a time. The conduit contained a sense wire terminated at both ends in the characteristic impedance (100 ohms) of the conduit-sense-wire transmission line. The ratio of the sense-wire current to conduit current was monitored as a function of both time and frequency to measure the transfer characteristics of apertures, rusted couplings and unions, and thin flexible sections of conduit (flex-joints). The coupling through apertures was observed by first increasing the length of a 0.040-in.-wide transverse slot in the conduit from 1 to 5 in. and then increasing the slot width from 0.040 to 2 in. The coupling through rusted connectors was investigated at currents both below and above the threshold currents required to produce arcing across the rusted surfaces. It was considered necessary to investigate nonlinear effects, such as arcing, because the field tests using PLACER are conducted at currents far below the threat-level currents which could cause arcing.

Based on the laboratory studies, the following general statements can be made concerning the coupling of EMP induced currents through conduit flaws:

1) Below 10kHz, the thin-wall flex-joints provide roughly 100 dB of shielding and with increasing frequency the shielding improves considerably. The low frequency shielding is directly proportioned to the wall thickness of the flex-joint.

2) Coupling through apertures increases linearly with frequency. The magnitude of the coupled current (although quite small in the EMP frequency range) is proportional to the third power of the circumferential length and to the first power of the longitudinal length.

3) A properly installed clean coupling or union provides more than 140 dB of shielding. However, if the joint is rusted or dirty so that no metal-to-metal contact is provided, and if arcing does not occur, then the resulting flaw impedance (which can be very

large in the case of rust) is predominantly resistive. In this case, the induced sense-wire current waveform is nearly identical to the exciting conduit waveform. When the conduit current is sufficient to induce arcing, the ratio of the sense-wire current to conduit current is reduced, although the two current waveforms in this case are quite dissimilar. Thus, the onset of arcing functions as a protecting mechanism by reducing the flaw impedance. Although most of the rusted joints studied were observed to arc, the experimental results indicate that it is not possible to predict a threshold conduit current at which arcing will begin.

4) In performing a threat-related analysis using PLACER test data, the visual inspection of the data identifies the flaw as being either an aperture flaw or a joint-type flaw, and the amplitude of the PLACER data fixes its magnitude over the frequency range of the PLACER test data. This amplitude coupled with the frequency dependence common to the class of flaw provides the frequency-dependent flaw impedance for a convolution integration with the threat conduit current. For a joint-type flaw, this frequency dependence is

$$(4) \quad Z_F = \text{Constant}$$

For an aperture flaw, the frequency dependence is

$$(5) \quad Z_F = k\,i\,w\,,$$

where k is a constant and i is $\sqrt{-1}$. The frequency dependence of a flex-joint is also known (4). However, the likelihood of detecting one exhibiting the referenced frequency dependence is remote, even in the extreme case of corrosion, since apertures would appear long before the wall thickness would become thin enough to produce a measurable flaw. Corroded flex-joints would therefore first appear as aperture flaws. The conclusion of the testing of the various types of flaws was that only circumferential joint-type flaws were important (e.g. broken conduit, rusted couplings, or other flaws which introduce a significant flaw impedance into a conduit), and for these, the flaw impedance is a constant over the frequency range of interest.

THE FIELDED PIM TEST USING PLACER.--The testing was conducted in two phases using PLACER in a 30kV cart-mounted single-loop configuration with an on-board power supply powered by a small 12-V battery. In the first phase, the PLACER unit (fig. 8) was pulled along both sides of the conduit bank at a range of 9 ft between the center of the loop and the center of the conduit bank. The cables inside each conduit (power or LE and SO) were monitored using a

clamp-around current probe at the cable entry point to the RLOB or at a manhole. A current probe was connected to a voltage pulse level detector. The level detector was adjusted to give an alarm if current pulses above a predetermined sure-safe level were induced on the cable as PLACER was moved along the conduit bank. When a signal was detected above the threshold level, the location was noted and marked for subsequent flaw location. The second phase of testing consisted of precision flaw location in which PLACER was moved in a prescribed fashion (7) in the vicinity of the location where the flaw was detected, and measurements were made as a function of loop position by using an oscilloscope (fig. 9). Following the testing of all of the conduits at the missile fields (8), a threat analysis was performed (4), and those flaws which posed a potential threat to the system were excavated and repaired. The PLACER was then used again during repair operations (fig. 10) to verify adequate repair.

Figure 8. (Left) PLACER Flaw Detection at RSL Site.

Figure 9. (Right) Instrumentation for Flaw Location at RSL Site.

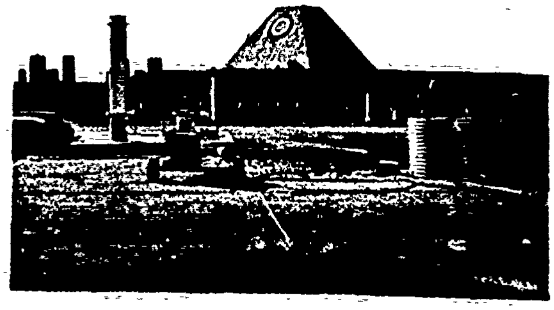

Figure 10. PLACER Conduit Repair Verification at MSR Site.

CONCLUSIONS.--The development of PLACER has provided the Army with a means for testing the shielding of buried conduits in hardened facilities for ABM or other systems. In the broader sense, the experience gained during the construction of the buried test models at Woodbridge and in the repairs at Grand Forks has provided an experiential base for constructing better conduit systems in future applications.

It was learned that it is relatively easy to join 2-in. conduits which were used for most of the power conduits in the SAFEGUARD site; consequently, there were relatively few problems in the power conduit system. One notable exception was a severe flaw which was the result of not joining the conduit at all at a point where a field-constructed nipple proved shorter than a gap which was simply taped over, rather than cutting a section that would fit to join the two sections together. The 4-in. conduits were a different matter. It was observed at Woodbridge that joining the sections together to a prescribed torque did not in itself insure that many threads would be engaged, unless someone relieved the moment by supporting the end of the conduit sections while they were being torqued tightly. Professional electricians employed by the contractor to assemble the 16-conduit test model did not achieve tight joints until they were coached in proper assembly. The explosive type of unions used in the construction of the conduits leaked water even when installed properly, but these unions were not necessarily any more likely than a coupling to induce an EM flaw.

The data developed during air-leak testing and conduit interior TV inspections were not correlatable with EM flaws. The latter proved to be of some aid as a supplement to PLACER testing to give precise locations of joints along the conduit run; however, it was not possible to detect shielding flaws by inspection.

The flaw characterization studies indicated that it would be best to weld the conduits to the couplings and unions in at least one spot to preclude possible joint-type flaws. A repair technique for joint-type flaws consisted of a sheet-metal clamshell formed to fit over a union or coupling. This repair was found to work well in eliminating shielding flaws when clamped to the bare conduit on each side with a liberal coating of conductive paste to insure good contact. Based upon the lessons learned and the PLACER technique, it is now possible to insure adequate conduit shielding effectiveness in mission critical conduits.

Although PLACER was developed for an EMP application, it should provide a solution to a wider class of shielding and nondestructive test applications for which shielding of buried conductors is desirable for reasons of security or protection from other EM threats.

REFERENCES

1. "CW Flaw Detection in Buried Conduits," EG&G Report AL-1020 (7 December 1973).
2. "Conduit Electrical Leak Detection Feasibility Test," McDonnell Douglas Report MDC G5061 (December 1973).
3. H. A. Roberts, E. Seijo , F. J. Agee, "EMP Testing of Buried Conduits, the Pulsed Dipole and Pulsed Transmission Line," Harry Diamond Laboratories TM-75-12 (September 1975).
4. H. A. Roberts, J. Capobianco, and F. J. Agee, "SAFEGUARD Buried Conduit Studies," Harry Diamond Laboratories TR (To be published).
5. "Ground Electromagnetic Pulse Effects, Phase IV Program Summary," Martin Marietta Report OR 316, Vol. I and II (April 1974).
6. "Spartan Launch Preparation Equipment Set Electromagnetic Pulse Susceptibility Analysis and Test Report, Phase IV," McDonnell Douglas Report MDC G5114 (February 1974).
7. "SAFEGUARD Protection Integrity Maintenance (PIM) Test Procedures for Buried Conduits," Harry Diamond Laboratories SR-75-1 through SR-75-5 (February 1975).
8. "SAFEGUARD Protection Integrity Maintenance (PIM) Conduit Test Data," Harry Diamond Laboratories BDM/W-75-258-TR (29 August 1975).